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HOW FAST α PARTICLES ARE EMITTED IN "MASSIVE TRANSFER" REACTIONS ?

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It has long been known that in, reactions induced by light projectiles, cross sections for emission of charged particles are enhanced as compared to the evaporation process. The angular distribution of such particles are strongly peaked in the forward direction suggesting a direct character for the mechanism[1]. In the last few years, new results have been obtained in that field. As the emitted particles have a velocity close to that of the beam, it is assumed that they come from a scission of the projectile as it reaches the nuclear field of the target nucleus. The remainder of the projectile then fuses with the target[2,3]. From cross section measurements, it has been deduced that these reactions occur for the highest impact parameters, higher than the critical value leading to complete fusion[4,5]. This has been confirmed by the high spin states reached in the residual nucleus[2,3], higher than in the complete fusion case. Another new data about these reactions is that even for heavier projectiles such as ^{32}S, ^{40}Ar, ^{86}Kr it is possible to observe direct particle emission, provided the beam energy is high enough[6,7,8]. In this paper, we report on measurements of γ multiplicities associated with α particle emission. We have deduced from our experiment that it was not possible in all cases to reach high spin states in the residual nucleus because of the angular momentum carried away by the α particle. Moreover we propose a critical parameter wich may allow to predict above which projectile energy direct particles emission will occur.

With the ALICE facility in ORSAY, two systems have been studied leading to the same compound nucleus ^{132}Ce at the same excitation energy : ^{116}Sn + ^{16}O at 125 MeV and ^{92}Zr + ^{40}Ar at 193 MeV. This second system, where no preequilibrium emission is observed, has been studied for purpose of comparison with the first system. In each case γ ray multiplicity associated with α emission has been measured. α particles were detected in a E (1500 μ) - ΔE (50 μ) telescope set at three angles 15° 45° and 128° in the case of the ^{16}O beam. With ^{40}Ar projectile, evaporation α particles were only studied at the backward angle. The channel reactions were identified by known γ lines in a Ge detector. A Ge spectrum associated with α emission is shown on fig.1. A coin-

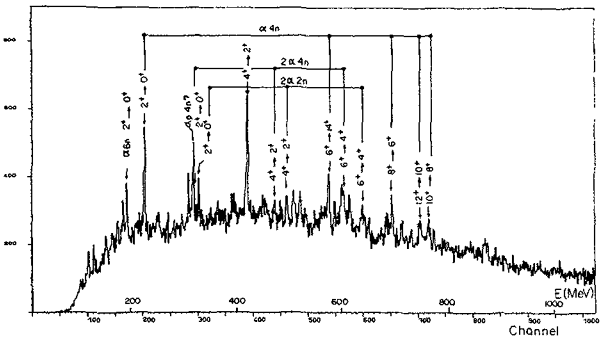

Fig. 1 : Ge spectrum coincident with α particles.

dence with the telescope gave the particle spectra for each channel. Center of mass α particles spectra

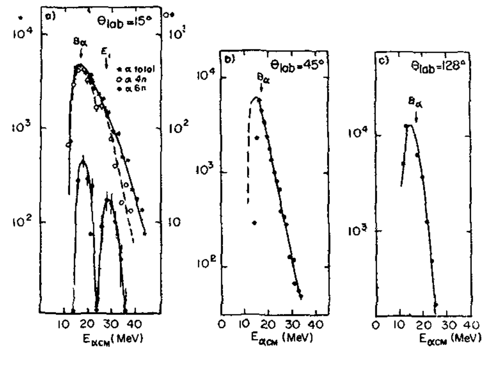

Fig. 2 : Center of mass α particles spectra at 15° and 45° for ^{116}Sn + ^{16}O(a-b) and at 128° for ^{92}Zr + ^{40}Ar(c). On part a are also indicated the α particles spectra coincident with γ lines identifying the α4n and α6n channels. B_α indicates the coulomb barrier for an α particle in the compound nucleus. E_i indicates the energy of an α particle having the same velocity as the incoming projectile. The low energy part of the 45° spectrum (1-b) is cut by a 120 μ Al absorber.

are displayed on fig. 2 for the three angles and on fig. 2.a and 3 at 15° in coincidence with specific Ge lines. The identification of the reaction

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channel is not sure for α5n and αp4n reactions but a characteric feature is the presence in each spectrum

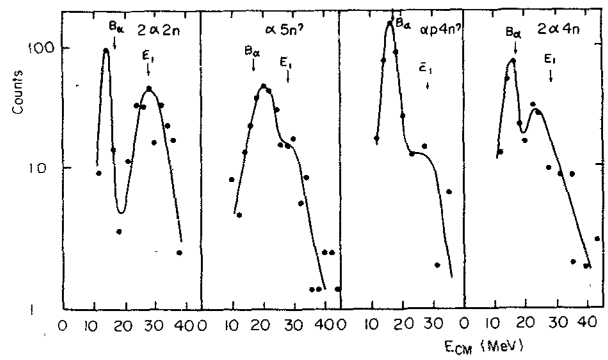

Fig. 3 : The same as fig. 1.a coincident with different Ge lines.

of two components. The low energy one is peaked around the value B_α which corresponds to the coulomb barrier for emission of an alpha particle from the compound nucleus. The high energy component is peaked at an energy close to the value E_i which corresponds to an α particle emitted with the velocity of the beam. The new feature is the separation of the two components for a given channel which is completely washed out when all the channels are summed up. On tables I and II we have indicated the γ multiplicity M_γ associated with α particles for both systems as a function of the α particle energy. On each table we have given the approximate l_i angular momentum of the residual nucleus at the top of the γ cascade. l_i has been deduced from M_γ through the relation $l_i = 2M_\gamma - 4$. From these tables we infer the following conclusions. i) for $^{116}Sn + {}^{16}O$ system contrary to the

Table I : γ multiplicity following α emission for $^{40}Ar + {}^{92}Zr$ system at $\theta_{lab\ \alpha} = 128°$.

$\bar{E}_{\alpha CM}$	12.5	14	16	>18
M_γ	19.5	23	25.5	23
l_i	39	41	47	43

Table II : γ multiplicity following α emission for $^{16}O + {}^{116}Sn$ system.

$\theta_{lab\ \alpha}$	15°				45°			128°
$\bar{E}_{\alpha CM}$	13.5	18	25	35	17	22	29	26
M_γ	9	9.5	8	7	19	17	14.5	22.5
li	14	15	12	10	34	30	24	41

results of Zolnowski et al.[2], high energy α particles lead to low spin states in the residual nucleus ($M_{\gamma 1}$ = 7-8), ii) at 128°, for both system, the spin of the state reached in the residual nucleus before γ emission is about the same $l_i \simeq 40\text{-}45\ \hbar$: α particles are evapored by the same initial angular momentum states. From table I we observe also that the more energetic the α particle, the higher the initial angular momentum. For $E_{\alpha CM} >$ 18 MeV, the multiplicity decreases slightly because of the higher angular momentum carried away by the α particle, (see fig. 4).

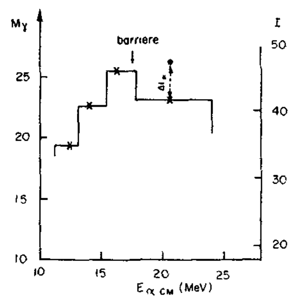

Fig. 4 : γ multiplicity and angular momentum in the residual nucleus for $^{40}Ar + {}^{92}Zr$.

iii) at 15°, the low energy component has a surprisingly low multiplicity $M_\gamma \simeq 9.5$ and not 22.5 as observed at backward angles. This means that at low energy another kind of α particles is added to evaporation α particles. These particles must be associated with a very low $M_{\gamma 3}$ multiplicity. Then the superposition with evaporation α particles ($M_{\gamma 2}$ = 22.5) will lead to a mean value $M_\gamma \simeq 9.5$. Moreover we know that they are strongly peaked in the forward direction as at 45° the multiplicity is nearly equal to the evaporation value. We have then three kinds of α particles : evaporation particles, high energy direct particles, low energy direct particles.

A very simple picture can be given to account for direct emission of high energy α particles : The incoming projectile is slowed down by the coulomb field between target and projectile to a velocity v_1. An α particle formed in the projectile at the moment of the collision has the same velocity v_1 as the mean potential of the projectile. If its lifetime inside the projectile is long enough as compared to the time for the remainder of the projectile to be stopped by its nuclear interaction with the target, the α particle can be emitted provided its energy $E\alpha_1 = 2v_1^2$ is higher than the sum $S_\alpha + B_o$ of the separation

Table III

System	E_{lab} MeV	$E_{\alpha 1}$ MeV	S_α MeV	B_o MeV	α directs	ref.	$E_{\alpha\,neck}$ MeV	$E_{\alpha\,periph}$ MeV	E_{exp} MeV
$^{10}B + {}^{159}Tb$	75	14.1*	4.4	1.8	yes	2	32	27	35-41
^{12}C + Ag	86	12.3	7.3	2.3	"	11	30	24	26
$^{12}C + {}^{154}Sm$	85	12.9*	"	"	"	2	30	25	28-33
$^{12}C + {}^{154}Sm$	109	21.1*	"	"	"	2	38	33	42-46
$^{16}O + {}^{116}Sn$	125	14	7.1	3.2	"	this paper	33	27	26
$^{16}O + {}^{58}Ni$	96	10.1	"	"	"	10			
$^{16}O + {}^{48}Ti$	310	37.6	"	"	"	10			
$^{19}F + {}^{153}Eu$	112	8.5*	4.0	3.5	"	2	26	21	23-29
$^{20}Ne + {}^{152}Sm$	119	8.2*	4.7	4.0	"	2	27	21	23-27
$^{20}Ne + {}^{152}Sm$	151	13.7*	"	"	"	2	32	27	24-31
$^{32}S + {}^{197}Au$	373	22.5	6.9	6.2	"	6			
$^{40}Ar + {}^{92}Zr$	193	4.4	6.8	6.7	no	this paper			
$^{40}Ar + {}^{58}Ni$	280	9.6	"	"	no	10			
$^{40}Ar + {}^{93}Nb$	400	18.6	"	"	yes	7			
$^{86}Kr + {}^{197}Au$	724	10.5	8.1	11.7	yes ?	8			
$^{14}N + {}^{207}Bi$	85	3.9	11.6	2.8	yes ?	10			
$^{14}N + {}^{207}Bi$	95	5.5	"	"	yes ?	10			
^{14}N + Ag	74	5.4	"	"	yes ?	11			
$^{14}N + {}^{103}Rh$	81	7.7	"	"	yes ?	9	25	19	17
$^{14}N + {}^{159}Tb$	115	16.4*	"	"	yes	2	35	29	35-39
$^{14}N + {}^{103}Rh$	121	17.9	"	"	"	9	38	29	22
$^{14}N + {}^{58}Ni$	148	25.1	"	"	yes	10			

* for theses cases, deformation of the target has been taken into account to calculate the coulomb field between target and projectile.

energy S_α of an α particle from the projectile plus B_o its coulomb barrier with the remainder of the projectile. On table III we have shown these values for different systems. Missing references will be found in ref. 10. All cases seem to be explained by this simple theory except $^{197}Au + {}^{86}Kr$[8] and systems with low energy ^{14}N projectile. In the case of ^{86}Kr, direct α particles seem to be of a different nature as they are correlated to the direction of the heavy fragment and, as such, cannot be emitted in an early stage of the reaction. For low energy ^{14}N induced reactions, the question remains open but in these cases, cross sections are much lower than that induced by other light projectiles in allowed conditions defined above. Moreover, the α energy is very often lower than the energy corresponding to the beam velocity. As the α particle is emitted in an early stage of the reaction, the residual system is not yet equilibrated, and the particle will be reaccelerated by the coulomb field of the composite system. This field depends on where the α particle is emitted. If the particle is emitted from the projectile region facing the target, the field will be higher, and also the final energy E_{neck} of the α particle. We shall call this case a "neck emission". If the α particle is emitted from the opposite side of the projectile, what we call a "periphery emission", its final energy E_{periph} will be lower but the particle can carry away more angular momentum. E_{periph} and E_{neck} are shown on table III for some systems. They have been calculated in the frame of the previous assumption of grazing collisions. We can explain the divergence between our results and those of Zolnowski and al.[2] : In their case, except for $^{20}Ne + {}^{152}Sm$ at 151 MeV, their α particle energy agrees better with a "neck emission". Then the α particle does not carry away too much angular momentum (about 15h are calculated with small variations depending on the system). This explains why high spin states are reached in the residual nucleus as the critical l_{cr} value is above 40 $\hbar$ in most cases. At the opposite, for $^{20}Ne + {}^{152}Sm$ at 151 MeV and for an $^{16}O + {}^{116}Sn$ system, the α energies agrees better with a "periphery emission". The α particle is then supposed to carry away about

30 ħ angular momentum. The spins then reached in the residual nucleus are lower. But up to now, we have not found any criterium to predict wether α particles will be emitted by the neck or the periphery.

In our experiment with ^{16}O projectile we also observed heavier nuclei with Z = 3 and Z = 4. Li nuclei, mainly ^{7}Li, are strongly peaked in the forward direction (more than α particles) but still observed at 128°. They are associated with a low multiplicity in the residual nucleus M_γ = 6.8 for $\overline{E}_{Li\ CM}$ = 35 MeV and M_γ = 6.2 for $\overline{E}_{Li\ CM}$ = 42 MeV at 15° and with only a small increase at 45° : M_γ = 7.8 for $\overline{E}_{Li\ CM}$ = 41 MeV. Energy spectra of ^{7}Li and ^{9}Be nuclei are displayed on fig. 5. If ^{9}Be spectrum is peaked at an energy corresponding to a Be velocity close to the beam velocity, ^{7}Li energy is much lower. It may be because ^{7}Li comes from an excited ^{11}B which deexcits promptly to ^{7}Li by α emission before reaching the detector. But we have no further information about this reaction mechanism.

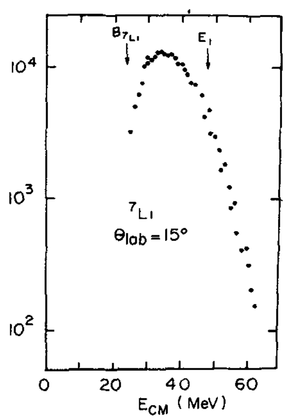

Fig. 5 : Center of mass spectra of ^{7}Li and ^{9}Be nuclei. B and E_i have the same meaning as in fig.1.

In this paper, we have shown that besides the evaporation α particles, there exists two other kinds of α particles, both associated with a direct mechanism : i) A high energy component, similar to what was known previously, seems to be rather well understood. In most systems it is possible to predict the energy above which these particles are emitted. Furthermore we have shown that these α did not always lead to high spin states in the residual nucleus. ii) A low energy component where the α particles leave very small angular momentum in the residual nucleus is still unaccounted for.

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